Metamorphic Robotic Systems for Space Exploration

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1 Abstract

Metamorphic robots with shape-changing capabilities provide a powerful and flexible approach to complex tasks in space exploration. Such robots can autonomously and intelligently reconfigure their shape and size to accomplish missions that are difficult or impossible for robots with fixed shapes and configurations. In this paper, we outline the vision of metamorphic robots for space exploration, and discuss the necessary technologies for making this vision possible. We also present approaches and evaluation criteria for robot/human interactions and discuss the significance and implications of this new concept and technology.

1 The Concept of Metamorphic Robotic Systems

Metamorphic robots are robots that can self-reconfigure their own shape, size, and configuration in order to accomplish complex task in dynamic and uncertain environments. These robots are highly desirable for space missions where tasks must be accomplished on remote planets without relying on large amounts of resources from the Earth. For example, to build an "explorative base" on the Moon, we could send a few of these metamorphic "super-robots" to do all the required tasks and use whatever resources are available on the Moon. Such a robot would become a digging machine if mining is required, or become a construction robot if habitat establishment is necessary. To provide transportation, such a robot would change to a wheeled vehicle if the terrain is flat, or a legged machine if it needs to climb a mountain or maneuver through a rocky area. Such robots are also capable of executing missions that are difficult for fixed-shape robots. For example, a single metamorphic robot can spread out as a set of autonomous smaller units for surface exploration, and then assemble into a large structure for transporting heavy objects. Since all the required capabilities are within the reach of such robots, we can eliminate the need for transporting many special-purpose instruments or machinery by space shuttles, thus greatly reducing the cost of space exploration.

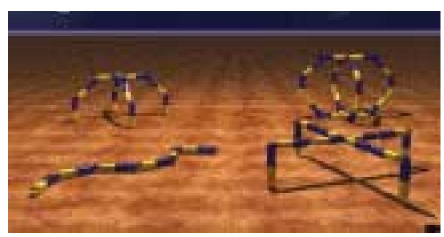


Figure 1 illustrates some capabilities of metamorphic robots, where a snake robot just passes through a pipe and is considering what configuration to use in order to manipulate the encountered cubic object. A unique and perhaps the most desirable feature of metamorphic robots is their robustness against damages to individual modules.

Modularized self-reconfigurable robots could perform self-repair when failures occur to individual modules by discarding the damaged modules via reconfiguration.

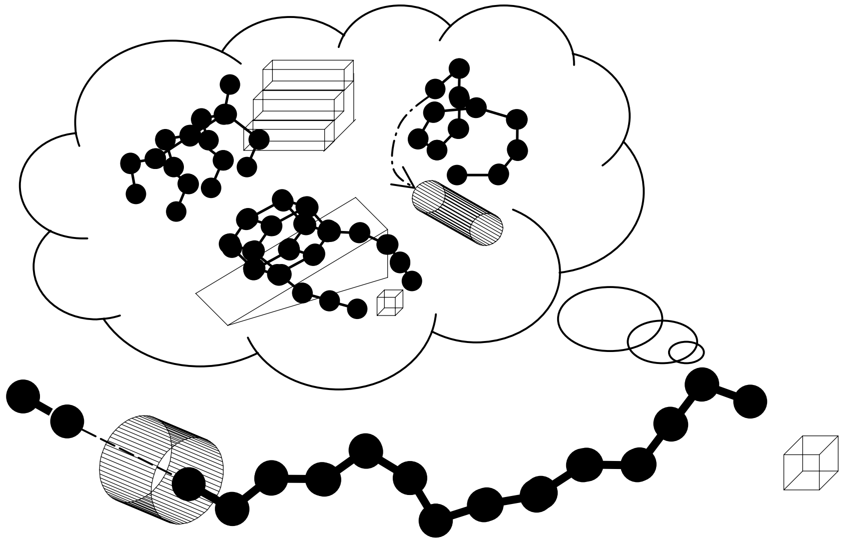


Figure 1: Example capabilities of self-reconfigurable robots

Using metamorphic robots, we can also construct **Metamorphic Machinery** for load management in space exploration. Specifically, we will demonstrate on a mobile platform that a crane machine can self-reconfigure into a three-armed apparatus that is capable of assembling universal joints for habitat construction. As illustrated in Figure 2, the platform has a set of "connectable bases," and initially a crane with 9-modules is on one of the bases. During self-reconfiguration, this crane will distribute and connect parts of its body to other bases (e.g., forming three smaller "cranes" on three different bases). Then two cranes will help the third one to build an arm with two side-branched fingers by connecting and leaving modules on the side connectors of the top module of the third crane. In the final configuration, these three arms on the base could work together to assemble universal joints that require at least three operating arms.

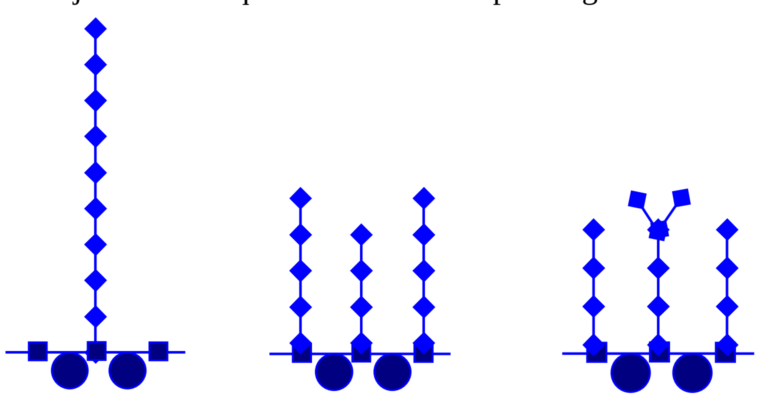


Figure 2: Metamorphic Machinery for Space Exploration and Inhabitation

2 Required Technologies for Self-Reconfiguration

Although metamorphic robots have a wide range of applications in space exploration, the control of such robots, however, is not a trivial task. Among many challenges, such as locomotion, reconfiguration, navigation, distribute signal processing, and decision-making, a metamorphic robot must intelligently select not only its behaviors but also its configurations. In addition, such dual coordination tasks must be addressed with the following fundamental constraints of self-reconfigurable systems:

1. Distributed Control and Fault-Tolerance. All elements in the organization are autonomous and intelligent, yet no single element should serve as the permanent brain. Otherwise damages to single elements may paralyze the entire organization.

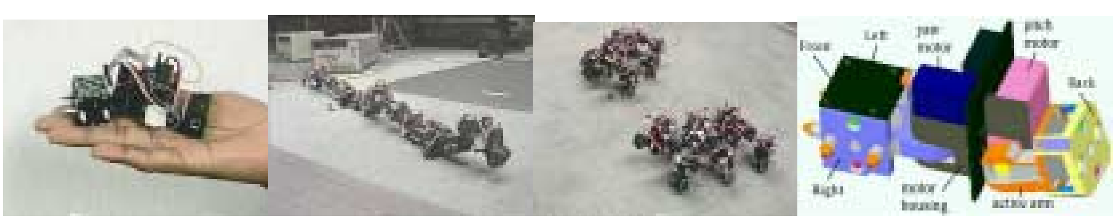
2. Dynamic Organization. Communication and coordination must deal with the dynamics of structure/network topology, and the proper behaviors of elements must be determined not by their identifiers/addresses but by their roles in the organization.

3. Asynchronous Coordination. No global real time clocks can be assumed always available for action coordination. Synchronization must be provided without such an assumption.

4. Scalability. Self-reconfigurable systems cannot assume at the outset how big and complex a functional organization will be. Thus any coordination mechanism must be scalable with the size and shape of the organization.

1.1 Hardware for Metamorphic Robots

In the past three years, we have built a new generation of self-reconfigurable robots called CONRO. The CONRO robot consists of a set of modular modules that can connect/disconnect to each other to form different complex structures for different tasks. Each CONRO module has a size of 1.0 inch^2 cross-section and 4.0 inch long and is equipped with a micro-controller, two servo motors, two batteries, four connectors for joining with other modules, and four pairs of infrared emitter/sensor for communication and docking guidance. In comparison of other existing metamorphic robots, the unique properties of CONRO robot modules are that they are autonomous and completely self-sufficient with own power, computational resources, and sensory and actuating devices, and they have the automatic docking capability to connect and disconnect with each other to form various shapes and size.



The above four pictures show a CONRO module in hand, an 8-module snake, two 9-module six-legged insects, and the detailed schema of a single CONRO module, respectively. For more information such as publications and movies of CONRO, please visit the web site http://www.isi.edu/conro. At the present time, 20 CONRO modules have been built. These modules can be connected to form various configurations including snake, caterpillar, quadruped, and hexapod. These configurations are capable of performing basic locomotion and self-reconfigurations. If funded, we plan to modify the modules to be water-sealed and mutually buoyant so that experiments can be performed in underwater environments.

1.2 Distributed Control Based on *Digital Hormones*

The main idea of Digital Hormones is that biological hormones are signals that do not require cells to have addresses or identifiers, yet can trigger different cells to perform different actions at different sites. Such signals propagate in a global medium, yet preserve the autonomy of each individual cells. They are different from the pheromones approach because they do not leave residues in the environment.

Joint with top researchers in biology, we envision that a self-reconfigurable system consists of two basic types of elements: a set of cells and digital hormones. Each cell is an autonomous agent that has certain properties. One major property is that it can secret digital hormones and has receptors to digital hormones. ***Digital hormones*** are typed elements that can be released from cells and captured by receptors of neighboring cells. Each type of digital hormone has its own density threshold and diffusion function. Digital hormones are propagated in the space from the higher density space to the lower density space with the ratio specified by the diffusion function. The propagation stops when the density is below a threshold. The receptors have different receptor types and can bind digital hormones with matching types. Receptors can be "used up" when bound to digital hormones, and can be created or deleted by cell's actions. Thus the number and types of receptors in a cell may vary in a life time. For simplicity, actions of cells are adhesion, migration, secretion, modification, and proliferation.

In the context of metamorphic robots, each self-reconfigurable robot is made of robotic cells (r-cells) that can connect and disconnect with each other to form different configurations or organizations. We assume such r-cells have the similar actions as those proposed above but can physically connect to one another. All r-cells have the same

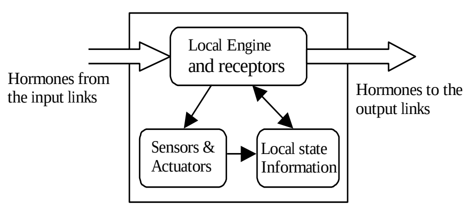


Figure 2: Internal structure of a r-cell

internal structure as shown in Figure 2, where software and hardware are constructed to simulate the biological receptors and the relevant part of decision-makings process. A local engine with a set of receptors can examine the incoming signals received from its active links, and decides if any local actions should be taken. Such actions include activating local sensors and actuators, modifying local receptors or programs, generating new digital hormones, or terminating digital hormones. Just as a biological cell, a r-cell's decisions and actions depend only on the received hormones, its receptors, and its local information and knowledge.

We represent a configuration of r-cells as a graph, where nodes are r-cells and edges are established connections. For example, a single CONRO-like r-cell with four potential connectors can be represented as the graph shown in Figure 3(a) where all four connectors are open. A graph for a snake-like chain of four r-cells can be represented as a graph in Figure 3(b), a 6-legged insect in Figure 3(c), and a system with two separate robots with a remote communication link (dashed line) in Figure 3(d). In general, an organization of r-cells can be an arbitrary graph with r-cells having different number of connections.

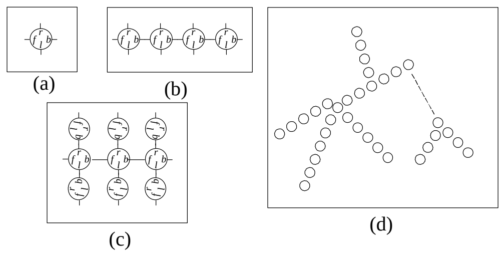


Figure 3: Examples of r-cell Organization

The digital hormones can be used to accomplish the communication, collaboration, and synchronization among r-cells. From a computational point of view, a digital hormone is a message propagating in the r-cell network and it has three important properties: (1) a hormone has no destination; (2) a hormone has a lifetime; and (3) a hormone contains codes that can trigger different actions at different receiving r-cells.

To illustrate the application of DH-Model in metamorphic robots, consider an example how digital hormones are used in self-reconfiguration. Figure 4 illustrates a situation where a metamorphic robot with seven r-cells changes from a quadruped (a four legged structure) to a snake. In this figure, a r-cell is represented as a line segment with two ends: a diamond-shaped end (the back link) and a circle-shaped end (this end has three possible links: the front, left and right). The robot must change from a legged configuration (at the top-left of the figure) into a snake (at the bottom of the figure). To do so, this robot must perform the “leg-tail assimilating” action four times. To assimilate

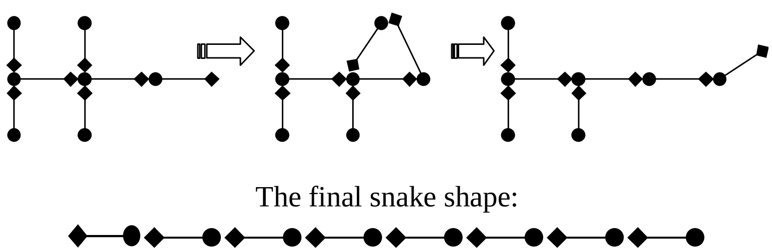


Figure 4: Reconfiguration from Quadruped to Snake

a leg into the tail, the robot first connects its tail to the foot of a leg and then disconnects the leg from the body (shown at the upper part of the figure). Just as in any r-cell organization, each r-cell in the robot determines its role based on its local state information including its own neighboring connections.

Using digital hormones, the entire reconfiguration procedure starts when one (and any one) of the r-cells generates a reconfiguration digital hormone LTS (Legs To Snake).

Digital hormones	Actions
LTS	Start the reconfiguration
RCT_1, RCT_2, RCT_3, RCT_4	Legs are activated
TAR, RCT_2, RCT_3, RCT_4	The tail inhabits RCT, and leg1 determines RCT_1
ALT, RCT_2, RCT_3, RCT_4	The tail assimilates leg1 and then accepts new RCT
TAR, RCT_2, RCT_4	The tail inhabits RCT, and leg3 determines RCT_3
ALT, RCT_2, RCT_4	The tail assimilates leg3 and then accepts new RCT
TAR, RCT_2	The tail inhabits RCT, and leg4 determines RCT_4
ALT, RCT_2	The tail assimilates leg4 and then accepts new RCT
TAR	The tail inhabits RCT, and leg2 determines RCT_2
ALT	The tail assimilates leg2 and then accepts new RCT
$\emptyset$	End the reconfiguration

This LTS digital hormone is floating to all r-cells, but each r-cell's reaction to this LTS digital hormone will be different depending on the receiver's role in the current configuration. For this particular digital hormone, no r-cell will react except the foot r-cells, which will be triggered to generate a new digital hormone RCT (Requesting to Connect to Tail). Since there are four legs at this point, four RCT digital hormones will be floating in the system. Each RCT carries a unique signature for its sender. No r-cell will react to a RCT digital hormone except the tail r-cell. Seeing a RCT digital hormone, the tail model will do two things: acknowledge the RCT by sending out a new TAR (Tail Accept Request) digital hormone with the signature received in the RCT, and inhibit its receptor for accepting any other RCTs. The new TAR digital hormone will reach all r-cells, but only the leg r-cell that initiated the acknowledged RCT will react. It first terminates its generation of RCT, and then generates a new digital hormone ALT (Assimilating a Leg to the Tail) and starts the required reconfiguration action (see (Shen 2000) (Shen 2001) for the details of this compound action). When seeing an ALT digital hormone, the tail r-cell will terminate the TAR digital hormone and start actions to assimilate the leg. After the action is done, the tail r-cell will reactivate its receptor for RCT digital hormones, and another leg assimilation will be performed. This procedure will be repeated until all legs are assimilated.

As we can see from this example, applying DH-Model to metamorphic robot control results in a number of advantages. First, the method works in many different configurations. In our current example, it will work independent of the number of legs in the system and how long the tail is. Second, the digital hormones are naturally organized in hierarchical structures. For example, a single LTS can trigger a level of activity managed by the digital hormones RCT, TAR, and ALT. One ALT will trigger another level of activity for assimilating a leg using another set of digital hormones (we did not show the details of this level in this example). Third, digital hormones allow global actions to be totally distributed to individual members. All r-cells have total autonomy in deciding their local actions, generating or terminating hormones. This allows on-line reconfiguration where a robot can maintain its function when merging or disconnecting with other robots. Fourth, this approach is de-centralized and any r-cell in the configuration can serve as the trigger of the reconfiguration. It is more efficient than centralized approaches because one single digital hormone is sufficient to trigger and coordinate all actions of all r-cells.

1.3 Configuration-Adaptation for Environments and Tasks

Self-reconfiguration in a dynamic environment is a very challenging problem. In order to change its current shape to fit the environment for missions, a self-reconfigurable robot must sense its surroundings and evaluate its current configuration to see if it is suitable for the mission goals. If not, the robot must search through the space of possible configurations, and find one that is appropriate for the current situation and then change its shape to that configuration. For example, if a legged robot must go through a thin pipe, it must realize that the size of its current shape is too large for the pipe and it must search through the configuration space and determine that it must reconfigure into a snake. Clearly, various coordination tasks must be solved in this process. These include how to represent, research, evaluate, select, and execute configuration changes.

Since each configuration is represented as a graph, we can represent the *space of configurations* as a state space of graphs. In this search space, each state is a configuration graph and it can be changed to another state through an operator. An operator is a dock/disconnect action that can either adds a new edge or deletes an existing edge. For example, by connecting the tail to the right-rear foot, a four-legged robot can become a configuration of three legs with a looped tail. Note that module types capture the important configuration properties of modules and such information can be exploited to evaluate the fitness of configuration to the current environment and mission.

Configuration graphs in this search space are evaluated by an evaluation function. This function takes a set of configuration properties and a set of environmental properties and returns a value in a total ordered domain. The configuration properties include the configuration's size, elements' types, maneuverability, energy consumption, and functions, while the environmental properties include the nature of the terrain (rugged, smooth, tilted, flat, and so on), and the height of the obstacle, and the size of the passage (e.g., the height of a tunnel or pipe). We assume these properties are sensed from the environment by sensors.

Thus, once facing a new situation, a self-reconfigurable robot first discovers its current configuration topology, evaluates the situation with its current configuration using the evaluation function. If the return value is below a threshold, it will search through the state space of configuration by mentally generating (using the operator) and testing (using the evaluation function) new configurations until a *satisficing* configuration is found. The entire process will be implemented in the Digital Hormone framework to exploit the advantages from both computational and biological systems.

3 Relative Human/Robot Roles

The effort to create a technology for robotic self- reconfigurability goes hand in hand with the possibility of assembly of robots by future astronauts in "Lego-like" fashion. On long-term missions, it is very likely that the execution of unpredicted tasks would become necessary or desirable. Reconfigurable robotics allows the possibility of a toolkit of robotic parts that could be snapped together into bodies of appropriate shape, with needed end-effectors and specialized locomotion strategies for the task at hand. These strategies could range from grappling on space truss structures to crawling into crevices or climbing peaks on planetary surfaces.

As we have seen above, reconfigurability needs to achieve two fundamental technological breakthroughs: one is the system of interfaces among the component modules, the second one is the planning ability to find any needed configuration and to execute the series of motions and module transfers that will accomplish the task.

For use in close cooperation with humans the second technological breakthrough is less crucial and can be viewed as a capability that can evolve in several stages depending on mission needs. The most basic of these stages could consist of a robotic kit of modules that could be quickly assembled by an astronaut to achieve a given purpose. In more advanced stages a new configuration could be communicated to the robot that would then have the ability to autonomously acquire the new desired shape. Finally, in the highest level of autonomy, the robotic system would have the ability to determine and acquire its best configuration on the basis of a particular goal to be achieved.

In each of these stages of autonomous self-reconfigurability would enable different and more advanced scientific exploration missions. Some examples are indicated below.

4 New Science Capabilities

The strength of reconfigurable robotics is adaptability, whether achieved autonomously or under astronaut guidance. This would allow for extended exploration through terrain of varying characteristics. In some areas, legged locomotion might work best, while in other areas exploration of crevices could be best achieved in snake-like crawling fashion. The same robot could reconfigure itself to perform either task. If water is found on another planetary surface, the same robot that could walk or crawl could also reconfigure itself or be reconfigured into a swimming device.

On space structures, repairs in unexpected locations could be facilitated by tailoring the robot shape to the particular needs. The robot might need to grapple to trusses, or it might need to insert itself into a small opening to reach a defective mechanism. The more flexibility we have in determining the shape and functionality of the robot the less need we have for costly human EVA.

One more extension of self-reconfiguration capabilities is in cooperative robotics, where teams of robots could not only cooperate on a single task but could join each other into large structures. A group of relatively small robots could for instance join together to form a bridge to allow an astronaut to pass over a large crevice or it could form a stair-like system to allow climbing very steep terrain.

Another example of these new capabilities is in the following automated drilling scenario, already proposed by one of the authors, for the Mars surface:

The concept we present addresses the 3 major technical issues facing all approaches to drilling on the Martian surface: limited power, limited mass and the need for robust autonomy.

Earth based systems need a large drilling platform to perform drilling in two stages. First a hollow casing needs to drill its way into the ground, then the drill proper is inserted into the casing and, using the casing as a guide, it drills a second tube into the ground. This second tube contains the “core” that is needed for studying the soil. This second tube is periodically pulled up to remove the core, and is then reinserted into the casing. The casing itself must be drilled deeper and added to from the top. The process is both energy intensive, and human intensive, since the entire casing and drilling assemblies must be rotated from the surface rig, and connecting different sections of casing is presently done by hand. Automating this process would most likely increase the mass required for the rig, as well as increase its complexity.

Other concepts involving plastic tubing pulled into the hole for casing have been developed, but these still present problems of mass, volume and power that we cannot address here.

In our concept we modify the casing to be light, self- assembling and a means for both transferring electrical power to the drill assembly and transferring core materials back to the surface.

This is how the process would work. Each casing element is a self-reconfiguring robot capable of two simple actions: a) changing shape from a collapsed form to a final hollow cylindrical shape, and b) turning some internal “wheels” or other actuators to cause the downward motion of new arriving casing elements and the upward motion of the core material.

Each casing element could simply be inserted in its collapsed form into the casing elements already in place, which would actively and “in concert” as in a “bucket brigade” lower the collapsed element to its bottom position, in a place just made ready by the action of the drill. In this position the new casing element assumes its cylindrical form and connects with the casing elements already in position above it.

Overall benefits

- **Energy Savings.** Energy consumption is confined to the drill bit area. Depending on whether active or passive lowering is chosen, very little or no energy is required to build the casing. In a sense, energy for this task will have been pre-stored in the spring-loaded mechanism that changes the shape of each element.
- **Mass Savings.** In a collapsed state, and with little mass, relatively large quantities of casing material can be made available at the drilling site allowing for deep drilling. The casing building scenario envisioned in this concept assumes that the casing would not be removable once in place, but robotic reconfigurability does allow for the possibility that each element could be “commanded” to collapse itself and be lifted back to the surface, thus allowing for reusability and transportation to a new drilling site.
- **Robust Automation.**
    - The only required surface activities are: 1) Hole initiation - basically a hole deep enough to allow for insertion of the first robotic casing element. 2) Insertion of collapsed casing elements into the hole – no precision or special connections required. 3) Retrieval of core materials.
    - Ordinary rover based robots should be able to perform these tasks without the need for a specialized automated drilling platform. All remaining automation is under the surface and is based on a few simple identical repetitive actions that could be exhaustively tested in harsh artificial and natural earth environments.
    - This example was presented in some detail to show that, while the horizon for reconfigurable robotics is relatively far into the future, it is already possible to focus the capabilites it will bring on very specific and recognized needs for the scientific exploration of planetary surface and sub-surface.

5 Conclusion

We have presented a vision for a revolutionary robotic technology that could greatly enhance human capabilities in space and enable a new range of scientific activities and planetary exploration. In particular, this technology opens the possibility of constructing robots that can change their shape and functionality, thereby affording extreme adaptability to new tasks and changing environmental constraints. Modules that demonstrate this possibility have already been built in Dr. Shen's laboratory. Such modular systems could be employed by astronauts to construct robotic devices suited to new tasks. At a more advanced stage, this technology could allow for autonomous reconfiguration, and this possibility has also been demonstrated with the concept of "Digital Hormones", a communication and control system inspired by biology that provides each module with the information necessary to decide on needed reconfiguration actions. Finally, we gave an example of how this technology could enable a completely new approach to planetary subsurface exploration, in the form of a deep drilling system capable of self-assembly. Although speculative, this example is illustrative of the revolutionary approaches to exploration that could emerge from a mature robotic self-reconfiguration technology.

6 Acknowledgement

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